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Telescience is the approach and collection of tools that enable productive scientific activity to be carried out using remote resources. By using interactive high-performance telecommunication links between space-based laboratories and facilities, on-orbit crew, and geographically dispersed ground-based investigator groups, facilities such as Space Station become an accessible and integral part of the research environment. In this paper, we describe an innovative program of rapid prototyping testbeds aimed at evaluating and validating telescience modes of operation and the technologies to support them. Particular attention is given to three testbeds evaluating remote instrumentation monitoring and control, expert systems in support of the interaction between the principal investigator and the astronaut, and telerobotics in support of fluid handling. In all of the testbeds, the application of these new technologies have been shown to improve scientific productivity.

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Introduction and Summary

Experiments in space differ from those in a solely ground environment in a number of ways. Lead times for planning are long, the expense is high, and the planning often involves large scale cooperative efforts. Scientists are isolated from their experiments in three dimensions: time, distance, and managerial levels (the latter in part because of the perceived requirement to filter interactions between scientists and their experiments due to safety considerations.) The ability to recover from even minor failures of equipment or to replan to take advantage of serendipitous events is limited.

This state of affairs has reduced the inherent attractiveness of space science. This situation must not and need not continue. To overcome these obstacles, scientists must be able to plan and conduct space experiments using tools and procedures in their own laboratories. The end-to-end process of scientific research must incorporate both the scientists' laboratories and space facilities in a smooth and evolutionary process.

A goal then is to make space science more closely emulate ground practice while still not violating safety and overall mission goals

Telescience is the label applied to the approach and collection of tools aimed at enabling this mode of operation. Telescience represents an orderly way of doing science at a distance.

What is Telescience

The SESAC Task Force on the Scientific Uses of Space Station (TFSUSS)* has used the word *telescience* to refer to the concept in which interactive high-performance telecommunication links exist among the space-based laboratories and facilities, the on-orbit crew, and geographically dispersed ground-based investigator groups. Instead of being a remote outpost, Space Station is then an accessible and integral part of the research environment. The distributed interaction is meant to include ALL members of a user team; in space and on the ground, and may involve either manned or automated operations. For convenience, Telescience has been broadly divided into three components:

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* Chaired by P. Banks of Stanford University

Teledesign - the ability to send drawings, documents and specifications, to perform interactive design with remote facilities, and to conduct interface and other tests of instruments by remote computer access.

Teleoperations - the ability to conduct remote operations by making rapid adjustments to instrument parameters and experiment procedures in order to obtain optimum performance or to take advantage of serendipitous events.

Teleanalysis - the ability to access and merge data from distant sources and to perform analyses and studies on computers that may be located at other institutions.

Telescience is not a new concept. Indeed, many past and current science activities, (e.g. seismography, remote astronomical observation using ground observatories, operation of the Viking and Voyager probes) successfully operated with the investigator remote from his/her experiment. There has, however, been no systematic methodology nor an integrated set of capabilities available for the practice of telescience in space or elsewhere. Telescience represents an orderly way of doing science at a distance.

The space science community is facing a fundamental choice of how to conduct business in the Space Station era and beyond. At one extreme, space experiments could be "just like working in your own laboratory." Spacelab, which permits more scientist interaction with the flight experiments than previously possible, amply demonstrates the potential advantage of flexibility in performance of space science investigations. At the other extreme, in order to assure safe and effective operation in a complex and dangerous environment, space experimentation could continue to entail a great deal of advanced and cumbersome planning and control. To date, because of the limited computer and communications capabilities supporting remote interaction, there has been no option but to lean towards the latter approach. With the rapid evolution of such tools taking place, we now have an opportunity to strive toward a more flexible and effective mode of operation.

Fundamental physical limits (e.g. time delays) and engineering/cost limitations (e.g. communication bandwidth and limited human resources in space) make the application of advanced technologies not merely desirable but essential for future NASA missions, including Space Station, Mars Rover, and the Great Observatories. In its March 1986 Summer Study Report, the TFSUSS recommended that NASA initiate a program whereby university researchers would conduct rapid prototyping testbeds employing new telescience technologies and ideas. From this program would emerge functional requirements for the Space Station Information System (SSIS). These testbeds would be specific research experiments within the scientific discipline areas that will use Space Station laboratories.

The rapid prototyping testbeds are not like a typical testbed. Rather than being used to evaluate and integrate systems on the way to deployment, the rapid prototyping testbeds constitute a technology evaluation environment. They allow users to interact with advanced technologies in the conduct of scientific research in order to develop the required base of experience to permit development and evaluation of requirements and specifications.

NASA responded to this recommendation by instituting a Telescience Testbed Pilot Program (TTPP)[1]. Several scientific experiments using advanced information processing and communications technologies are being conducted and the results evaluated to determine the requirements and their priorities. This will provide quantitative evidence as to the relative importance of different functions in the SSIS and their required performance. Furthermore, it will allow a representative set of users from various disciplines to gain experience with advanced technologies and their application to science. The latter will result in a scientific community able to contribute to NASA's review of SSIS requirements and proposed design prior to development of Space Station hardware.

Telescience Testbed Pilot Program Overview

Fifteen universities, under subcontract to the Universities Space Research Association (USRA), are conducting a variety of experiments representative of the scientific research of the Space Station era and aimed at resolving critical issues in space station operations concepts and information system design. The goal is to allow scientists to interact with potential space station technologies in a manner that will allow resolution of design and specification questions without having to wait until space station hardware is available. As NASA and the scientific community develop advanced concepts for scientific operation (such as the use of resource envelopes for allocation and scheduling of resources on shared platforms), there is a need to investigate the technical and procedural issues involved. For example, as there is more emphasis on both autonomous systems and the ability to support remote operations, the question arises as to the relationship between those two capabilities. What is the appropriate overall system architecture that allows the Principal Investigator, ground crew, flight crew, and onboard experiment to be tied together in an effective and meaningful manner?

The following is a short synopsis of the testbed experiments currently ongoing as part of the TTPP.[2]

University of Arizona (L. Schooley, F. Cellier, and D. Schultz) is conducting two experiments. The first involves teleoperation of a forerunner of the Astrometric Telescope Facility, which will be an attached payload for Space Station. The second is developing systems and software for remote fluid handling in support of microgravity and life sciences. Arizona is also participating in the SIRTF project described below.

University of California, Santa Barbara (J. Estes and J. Star) is exploring teleanalysis of large dynamic data sets for earth sciences. This investigation includes the test and evaluation of data interchange standards and knowledge based techniques for assisting remote access.

University of Colorado (E. Hansen, R. Davis, and G. Ludwig) is conducting three experiments. The first involves distributed and interactive operation of an astronomy telescope and its instrumentation at a remote ground observatory and addresses a range of teleoperations issues. The second, in coordination with UC Santa Barbara, Wisconsin, Purdue and Michigan, uses the interactive control opportunities and the science database from the Solar Mesosphere Explorer Mission to investigate coordinated teleoperations and teleanalysis issues. In the third area, researchers are prototyping and evaluating on-board operations management concepts to verify that teleoperations can function safely without command pre-checking.

Purdue University (R. Collier) is evaluating teleanalysis concepts using the Purdue Field Spectral Database accessed by a variety of small computers. It is also investigating methods for conducting campaign style experiments and computer data security issues.

Rensselaer Polytechnic Institute (R. Hahn) is establishing a testbed to determine experimentally the level of communications capability required to successfully perform remote controlled materials processing experiments of the Space Station era. Three different types of experiments will be tried with the cooperation of the Microgravity Materials Science Laboratory at Lewis Research Center.

University of Michigan (R. Volz and L. Conway) is experimenting with teleoperations of a Fabry-Perot Spectrometer combining human with autonomous control, forward simulation techniques to support telerobotics, and the effects of varying time delays in the control loop.

University of Wisconsin (V. Suomi and R. Dedecker) is providing a bridge from NSFnet to McIdas, allowing any TTPP participant with access to NSFnet to acquire existing meteorological products from McIdas.

Stanford University (M. Wiskerchen and R. Bush) is experimenting with a model Remote Science Operations Center linked to GSFC, JSC and MSFC using real data from Spacelab 2 to test multimedia Telescience workstations and simulate remote control, monitoring and multi-media conferencing.

MIT is conducting two experiments. The first (C. Oman, L. Young, and B. Lichtenberg)) is a Remote Life Sciences Operation using the KSC sled with multi-media tests and evaluation of real video needs and implementation options. They also (J. Elliot and R. Baron) are investigating the remote operation of a telescope at Wallace Observatory using a high bandwidth (T1) link and dissemination of data on campus-wide Project Athena network.

The Space Infrared Telescope Facility (SIRTF) team, consisting of Cornell University (T. Herter), Smithsonian Astrophysics Observatory (D. Koch), CalTech (T. Gautier), and University of Arizona (E. Young), are investigating several issues regarding telescience applied to a Space-based astronomical facility. They are evaluating distributed versus resource-centered models for development (teledesign) and remote access. The ability to interchange analysis software and perform in conference mode for design, operations and analysis will be evaluated. University of Arizona has a special interest in remote control and operations of a ground-based telescope to evaluate feasible degrees of automation, allowable time delays, necessary crew intervention, error control and feasible data compression schemes. Cornell University is investigating trade-offs between on-line local processing and processing at the user's home location as well as investigating the feasibility of establishing standard formats and analysis techniques. Smithsonian Astrophysical Observatory is using remote operation of Mt. Hopkins telescope to evaluate data transmission and dissemination options.

University of California at Berkeley (S. Chakrabarti) is extending control and simulation systems developed for the Extreme Ultraviolet Explorer (EUVE) to evaluate techniques for remote instrument control over local and wide area networks. Distributed development environments in use at Berkeley are being extended to facilitate coordinated development by cooperating institutions.

University of Rhode Island (J. Kowalski) is investigating a novel image compression technique with ''zoom'' capability to help progress from browsing to detailed analysis of selected areas using modest bandwidths from remote sites.

RIACS (B. Leiner) is integrating various networking and local computing capabilities into a ''telescience workstation'', intended to provide a local computing environment for telescience.

These experiments all share the characteristic that they are attempting to apply new technologies and concepts of science operation to ongoing scientific activities. To better explain the relationship between telescience, automation and robotics, and rapid prototype testbeds, we have selected three examples from the TTPP for more detailed discussion. The first example is the use of an advanced workstation environment to monitor and control remote instrumentation. The second example is the use of expert systems to support the astronaut payload specialist in carrying out experiments. The final example is the role of remotely controlled robotics for on-board fluid handling.

Remote Instrumentation Monitoring and Control

The job of exploring space and exploring from space is usually achieved by flying spacecraft that carry instruments designed by many different scientists drawn from science institutions all across the country and around the globe. In the past although the scientists involved in a mission were geographically dispersed, the operation of the science experiments had to be centralized due to technological limitations. Often scientists had to conduct their space experiments from a centralized mission control facility. If they chose not to spend weeks or months away from their home laboratories, the scientists had to delegate the operation of their instruments to controllers at the central facility.

A new way of conducting experiments in space is being developed that allows scientists to monitor and control their own space experiments from their home institutions. Providing sophisticated teleoperations capabilities to the space science community has been a goal of the University of Colorado's Laboratory for Atmospheric and Space Physics (LASP). Led by E. Hansen, R. Davis, and A. Jouchoux, LASP has designed the simple-to-use Operations and Science Instrument Support (OASIS) software package to provide scientists with capabilities previously only found in large mission control centers. OASIS communicates with science instruments, test equipment and spacecraft. It receives incoming data and translates the data into measurements in units meaningful to the scientist. OASIS checks the incoming data and alerts users to any conditions requiring their attention. If it is important to respond rapidly to a condition, OASIS can be directed to react automatically. It can, for example, shut down an instrument upon detection of an overvoltage condition.

OASIS has a sophisticated display capability that allows users to view data in real time in a variety of formats, including alphanumeric text, graphs and even symbolic representations like dials, gauges and switches. Users control their instruments through OASIS by entering commands in English-like phrases like "TURN ON HEATER." OASIS will convert these commands into the digital strings understood by the instrument.

Despite the wide array of functions provided, OASIS can easily be tailored for a particular application by the scientists and engineers who use it. Users tailor OASIS for an application by filling in a database that provides information to OASIS on the characteristics of the instrument that is to be controlled and the nature of the processing to be performed on the data returned by the instrument. Once the database is developed the users can write procedures in a special control language called CSTOL to perform, test, and implement operational sequences for their instruments.

OASIS can be used by scientists in conjunction with the other software they may have for analyzing their data. A common approach is to use OASIS for commanding an instrument and for acquiring the data from the instrument and checking and displaying the data in real time. The data are then transferred to other programs for further in-depth analysis.

OASIS is an example of the potential represented by modern computing and communications technologies. In the TTPP, OASIS is being evaluated in a number of scientific environments. LASP continues its evaluation in the control of SME. NASA Ames Research Center and RIACS are collaborating with Colorado to evaluate the role of OASIS in controlling remote life science experiments. Berkeley is investigating the role OASIS can play in controlling the EUVE satellite. Arizona is investigating OASIS in the context of remote telescopes and fluid handling (see below.) In each of these investigations, real science is being supported through the use of advanced/prototype technology.

In future missions like Space Station, scientists may have the opportunity to travel with their experiments into space. The teleoperations concepts embodied within OASIS will make it easier to monitor and control complex experiments from onboard as well as from the ground. Soon scientists will produce "smart" instruments that can make their own decisions about which data to acquire and how to acquire them. The same teleoperations concepts used in OASIS will be extended to make such autonomous instrument operation a reality.

Expert Systems in Support of PI/Astronaut Interaction

The role of the astronaut or payload specialist in the conduct of experiments on the space station will differ significantly for past practice. On the one hand, the extended crew duration will permit repeat tests and flexibility in protocol modification not available in previous short duration, fully-booked flights. On the other hand, the astronauts will be called upon to operate, interpret and repair a wide variety of instruments, many of which are outside his or her original field of expertise, and may this be unprepared to react to "off-nominal" situations. Ideally, the Principal Investigator (PI) would be present in the Space Station, or virtually present at his home laboratory, looking over the shoulder and whispering into the ear of the astronaut as the experiments proceed. Ideally the astronaut should be able to show the PI calibration and test data and confirm that all is well, or point out unexpected data and ask whether or not something is wrong - or if that data warrants a deviation from the nominal experiment to track down its origin. Ideally the astronaut would receive a last moment training update to prepare for each new stage of the experiment. Limitations on communication bandwidth and the reluctance of both astronauts and investigators to bare their souls and reveal their errors or misconceptions on open Air-to Ground channels make these ideal Telescience aspects impractical. An alternative to having the PI present in the Space Station, however, is to make his reasoning available to the astronaut locally by means of an Expert System in an on-board computer. This concept, which we term ''Principal Investigator in a Box'', or [pi], has been designed in terms of any astronaut intensive space experiment and initiated with a feasibility test for one particular Life Science experiment already flown on Spacelab. Its goal is to involve the astronaut fully as a scientist as well as an operator during the conduct of the space experiments. The project was initiated by L. Young of MIT during a sabbatical year at Stanford and Ames, in conjunction with S. Colombano, D. Rosenthal and P. Friedland of Ames, and N. Wogrin, T. Comfrey and G. Haymann-Haber of Stanford.[3] The test considered the operation of the Space Sled - a linear acceleration device used to assess astronaut sensitivity to acceleration. The same test was the subject of the related MIT/KSC Telescience experiment concerned with video bandwidth requirements for minimal PI involvement.

One of the[pi] tasks is simply to monitor the data and either assure the astronaut that the quality is acceptable or, if not, to categorize the problem and lead him through a diagnosis and trouble-shooting procedure. If the data quality is acceptable but the results are not what was anticipated, according to existing models known to the PI, then the data is potentially ''interesting.'' At this point the expert system must help the astronaut, and the real PI, to decide whether to note the fact and proceed as planned, or to look into alternative procedures to explore the new finding and determine when and how these procedures could be implemented. The [pi] also provides dynamic scheduling information, which takes into account not only the progress of an experiment relative to the pre-planned timeline, but also the experience from recent performances and the time required to repeat or insert new tests. The entire program is under control of a "protocol manager" which interfaces with the astronaut and the experiment in managing the advice giver. The real PI remains involved through ground dumps of the flight [pi] and selective monitoring and communication.

To this point a test case involving the measurement of human eye movements on the Space Sled, including trouble shooting and the categorization of data as "interesting" in terms of its correspondence to pre-flight norms, has been implemented, using a portable commercial shell which runs on small machines. Extensions to the visual-vestibular interaction experiments scheduled for future Space Life Sciences Spacelabs are underway.

Telerobotics in Support of Fluid Handling

Many planned and anticipated experiments in the microgravity and space life sciences areas will require fluid handling with special care to avoid spillage and to deal with bubble behavior is required. Toxic materials, in particular, require transfer in an isolated work station. While advanced techniques are available in ground facilities, such facilities have not been designed to accommodate reduced gravity. Furthermore, biotechnology experiments will require accurate control and measurement of fluid products.

The University of Arizona, under the leadership of L. Schooley, is exploring the use of robotics to ease the load on astronauts for routine fluid handling while at the same time assuring that the necessary degree of accuracy for scientific experimentation is maintained.[4,5] A commercially available robot is being used in a rapid-prototype environment. Modifications are developed to the robot itself to support the accuracies required and to operate in reduced gravity. Simultaneously, automated control mechanisms are being developed and evaluated. The mechanisms will support both local (payload specialist) and remote (ground crew or PI) control using high level commands.

To validate the approach, the evaluation is being done in the context of electrophoresis testing and pH measurement. Experiments have been performed on individual samples and mixtures of solutions prepared by a robot. To accomplish this experiment, a specialized syringe adapter was developed that is suitable for use in reduced gravity and can be handled by a robot gripper. This device provides accurate positioning of all syringes for robot pickup, injection of precise fluid volumes, and disposal of used syringes.

The software interface for the remote robot design consists of three parts: a human/computer high level macrocommand interface (an OASIS application) which allows the user to easily operate the laboratory from a remote location without having to be a fluent programmer, a machine/machine medium level command interface (intermediate language) which contains the set of commands internal to the system and enables the communication between the remote commanding computer (RCC) and the local controlling computer (LCC), and a machine/instrument low level command interface to the laboratory robot and the instrument rack. For the Scorbot used in this demonstration, high level commands are successively decomposed into series of lower level commands which finally map into the hardware interface language of the used equipment.[6]

NASA Ames Research Center is collaborating with Arizona and is evaluating their results for application to the Ames Space Life Sciences testbed.

Conclusion

Telescience represents an effective approach and set of tools for the conduct of scientific research in the future. It allows for full advantage to be taken of advanced platform capabilities consistent with safety and security considerations. This approach takes full advantage of flight crew, ground crew, and scientists working as a team in both the planning and operation of an experiment.

A&R in general and telescience in particular are every bit as critical technologies for advanced missions as such items as advanced propulsion systems or reentry vehicles. Without such technologies, NASA will not be able to conduct science taking advantage of the capabilities represented by such advanced missions as Space Station, Mars Rover, and Lunar Base.

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